

# On the $t\bar{t}$ forward-backward asymmetry

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Physics 290e, September 28, 2011

- Measurements
- Standard model
- Some model building
- LHC possibilities

My work: 1103.2757 with G. Marques Tavares & M. Schmaltz

1107.4090 with J-F. Arguin & M. Freytsis

# Measurements of $t\bar{t}$ production

- Spectrum and  $\sigma_{t\bar{t}} = (7.5 \pm 0.5) \text{ pb}$  agree reasonably well with the expectations

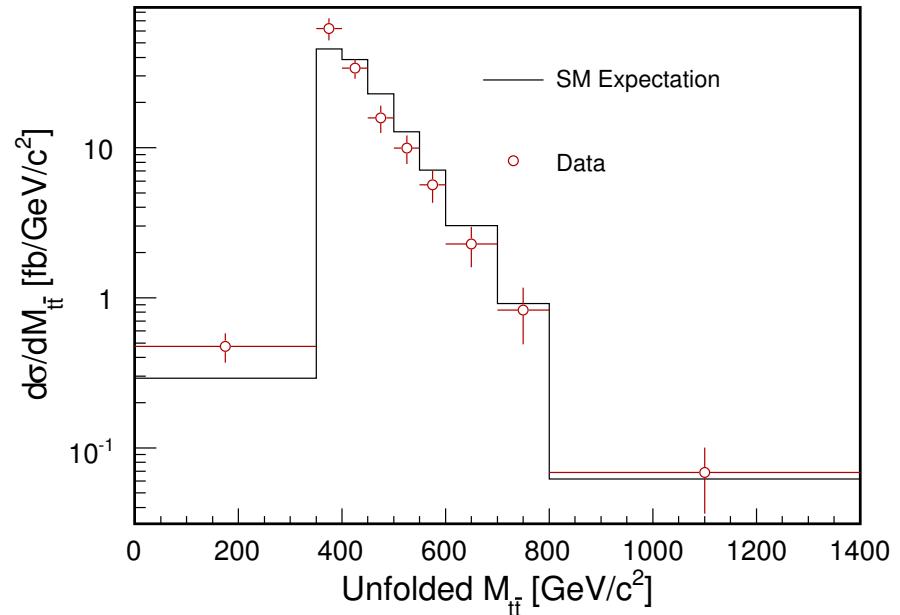
Spread in the theory literature:

$$\sigma_{t\bar{t}} = 7.2 \pm 0.8 \text{ pb} \quad [\text{Beneke et al., 1109.1536}]$$

$$\sigma_{t\bar{t}} = 6.5 \pm 0.3 \text{ pb} \quad [\text{Neubert et al., 1003.5827}]$$

$$\sigma_{t\bar{t}} = 7.2 \pm 0.4 \text{ pb} \quad [\text{Kidonakis, 1009.4935}]$$

NLO + different resummations — a conservative theory uncertainty ought to be substantial...

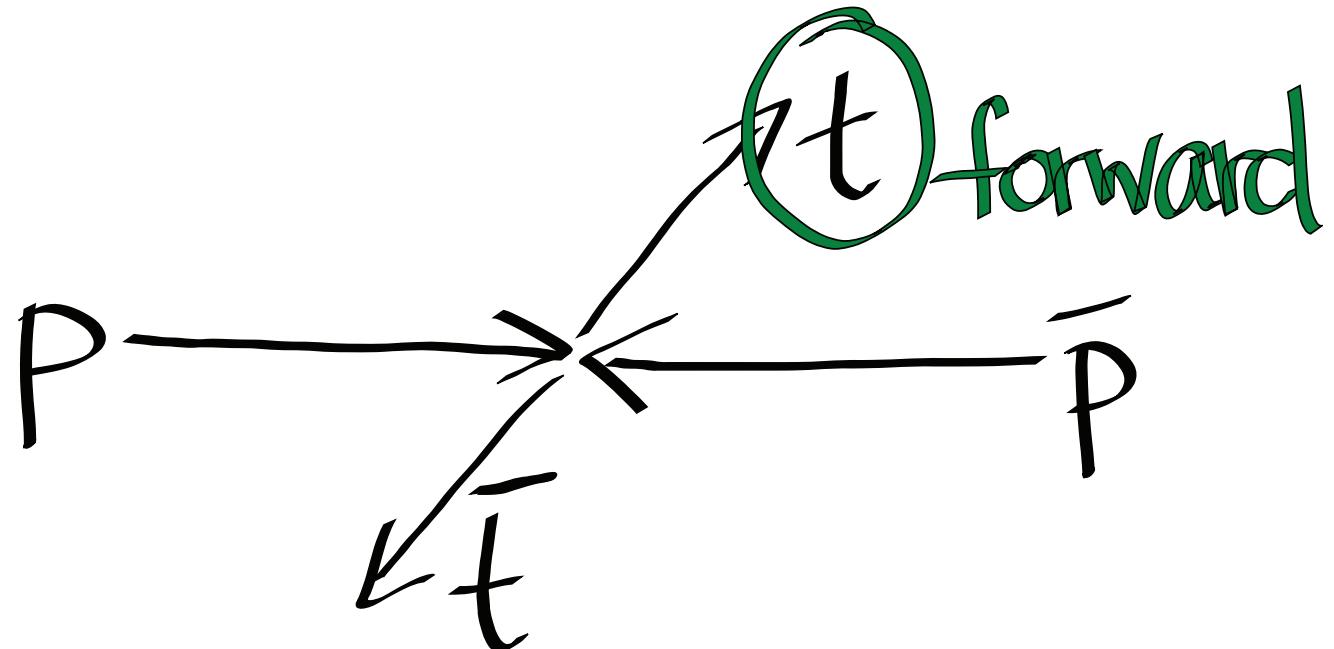


[CDF 0903.2850, only using  $2.7 \text{ fb}^{-1}$ ]

- ATLAS and CMS production rates are also consistent with theory predictions, with  $\mathcal{O}(10\%)$  uncertainties (on both the theory and the experimental sides)



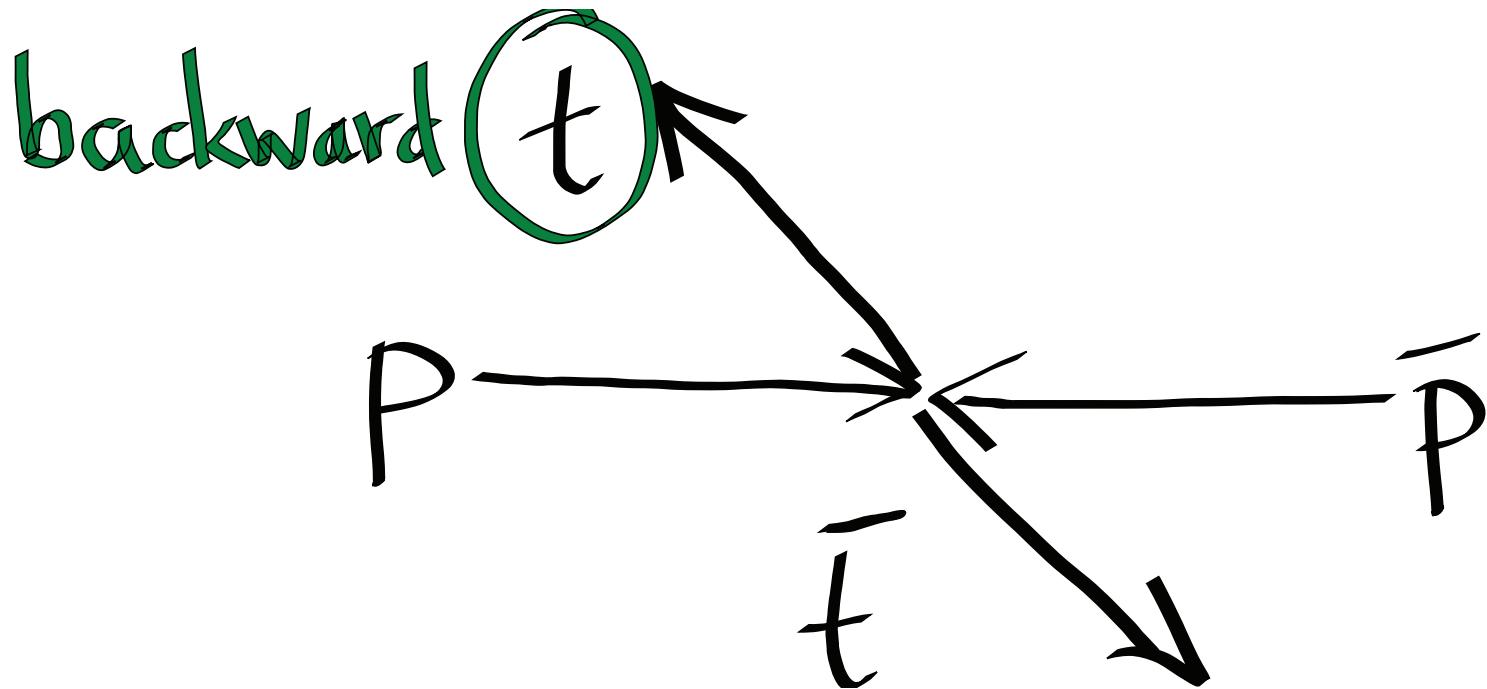
# Forward-backward asymmetry



$$A_{\text{FB}} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$



# Forward-backward asymmetry

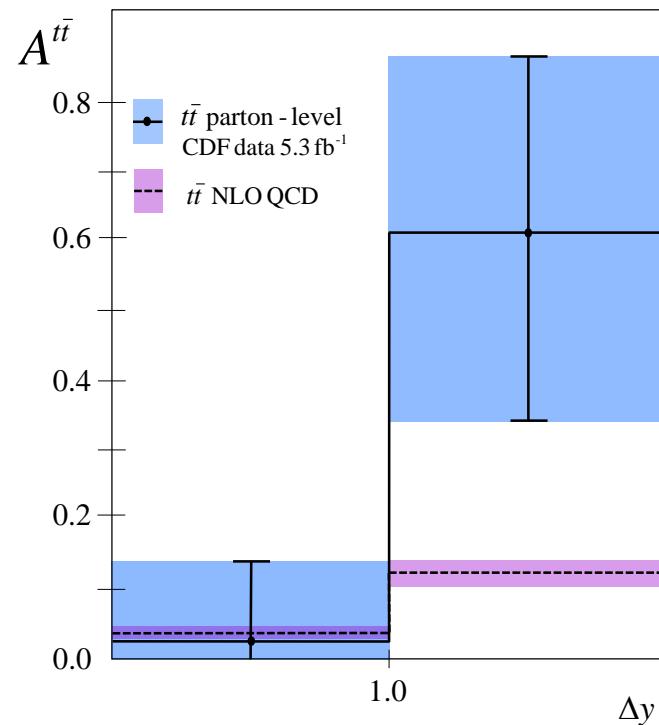
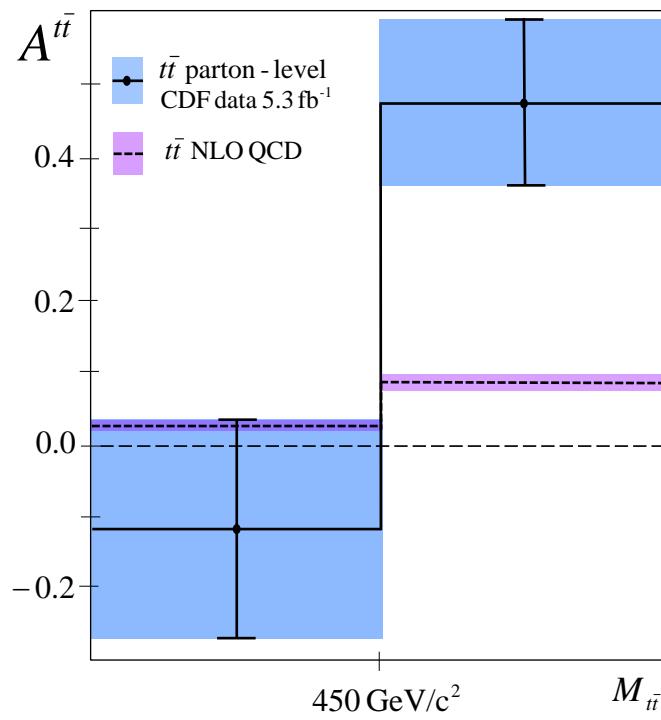


$$A_{\text{FB}} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$



# CDF forward-backward asymmetry

- CDF:  $A_{\text{FB}}^{t\bar{t}}(m_{t\bar{t}} > 450 \text{ GeV}) = 0.475 \pm 0.114$ ,  $A_{\text{FB}}^{t\bar{t}}(|\Delta y| \geq 1) = 0.611 \pm 0.256$



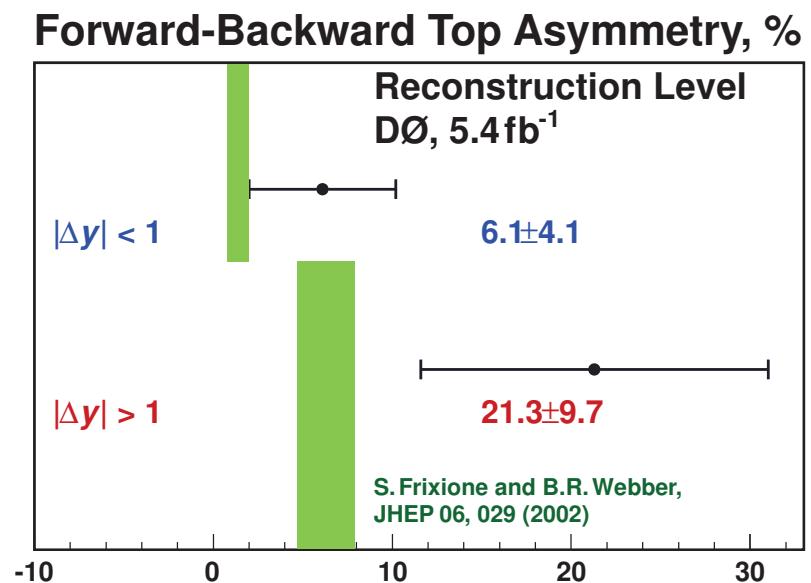
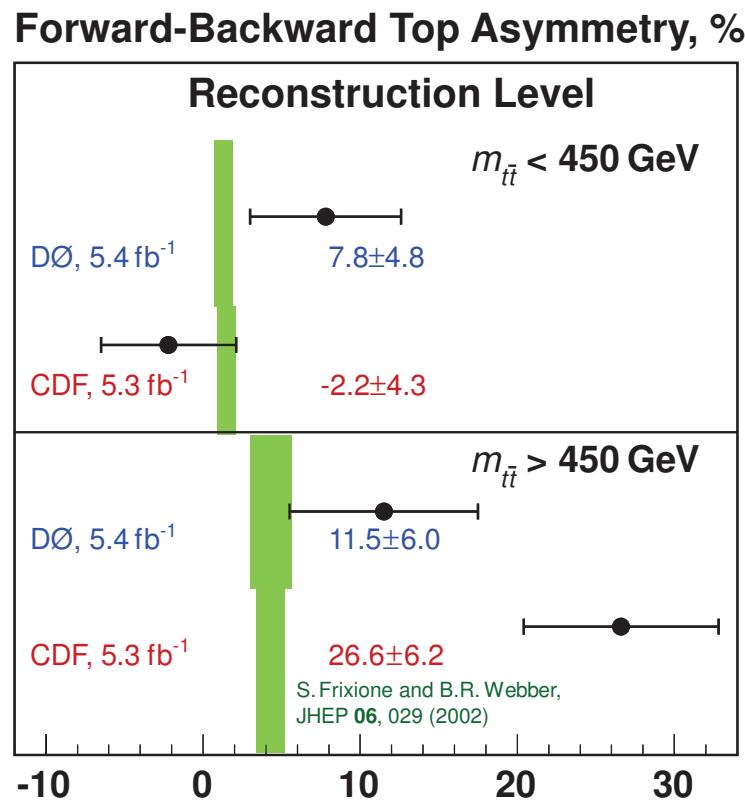
[CDF, arXiv:1101.0034 — over 120 citations...]

- Integrated over full phase space:  $A_{\text{FB}} = 0.158 \pm 0.075$ , CDF,  $5.3 \text{ fb}^{-1}$  [1101.0034]  
 $A_{\text{FB}} = 0.196 \pm 0.065$ , DØ,  $5.4 \text{ fb}^{-1}$  [1107.4995]



# DØ forward-backward asymmetry

- No  $m_{t\bar{t}}$  dependent results from DØ yet, with all the detector effects removed  
 ⇒ Comparison only possible at “reconstruction level”

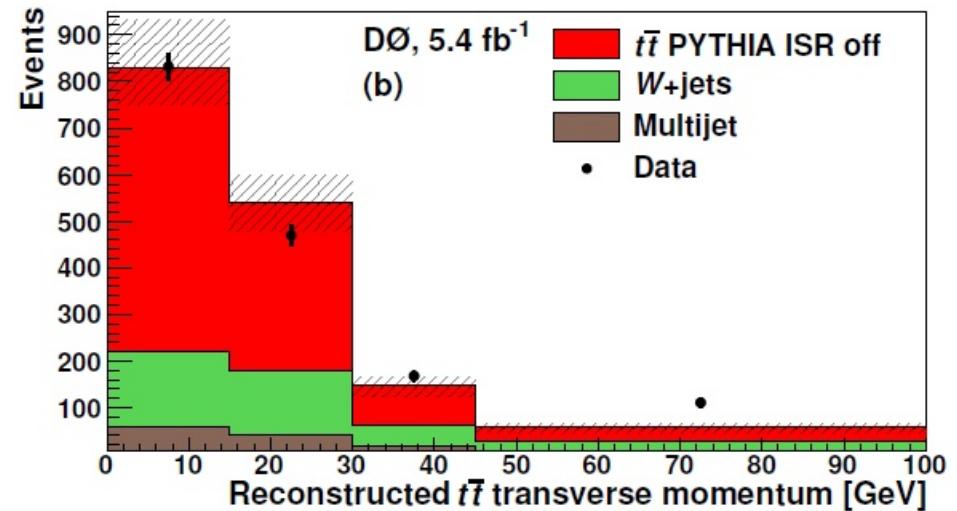
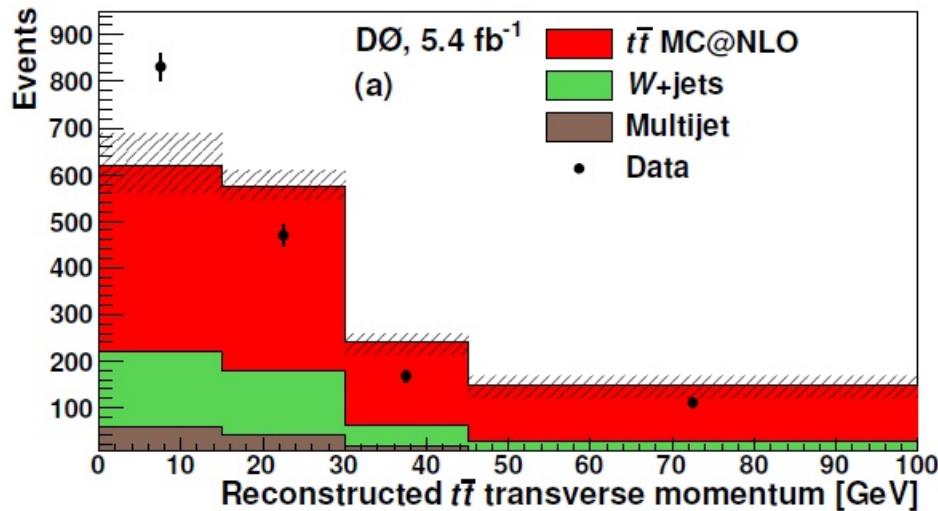


- No significant deviation between  $A_{FB}$  at reconstruction level.



# DØ — hint of problems?

- The correlation between  $p_T^{t\bar{t}}$  and  $A_{FB}$  may be large (MC)  $\Rightarrow$  check modeling of  $p_T^{t\bar{t}}$



Drastic change needed for simulation to match data — lower radiation is preferred

Gluon radiation may be mismodeled by MC@NLO+HERWIG — best agreement with PYTHIA ISR off (higher contribution from  $2 \rightarrow 2$  processes, e.g., Born+box?)

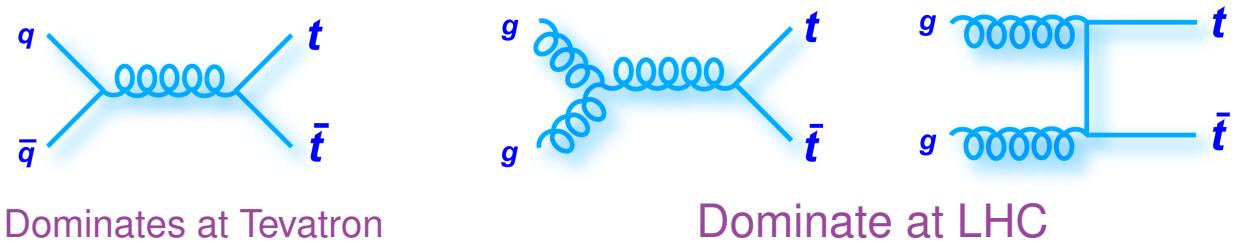


**standard model**

# SM prediction

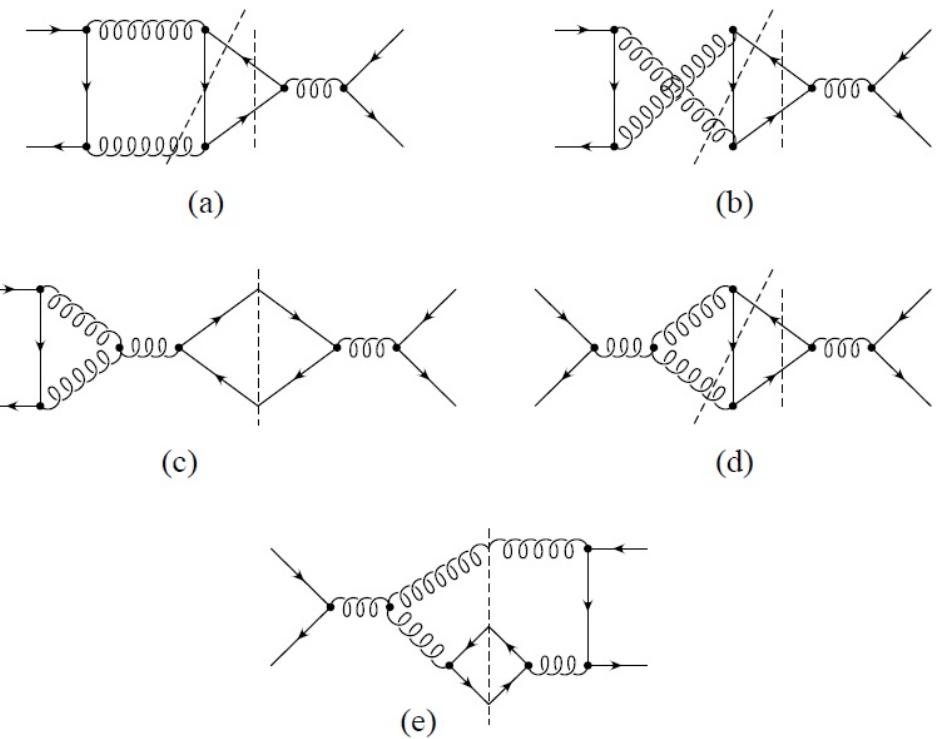
- $t\bar{t}$  production at leading order in QCD

No asymmetry generated



- Asymmetry is generated at next-to-leading order... squared amplitudes  $\Rightarrow$

$\sim$  interference of initial and final state radiation  
 $\sim$  different acceleration of color charge F vs. B



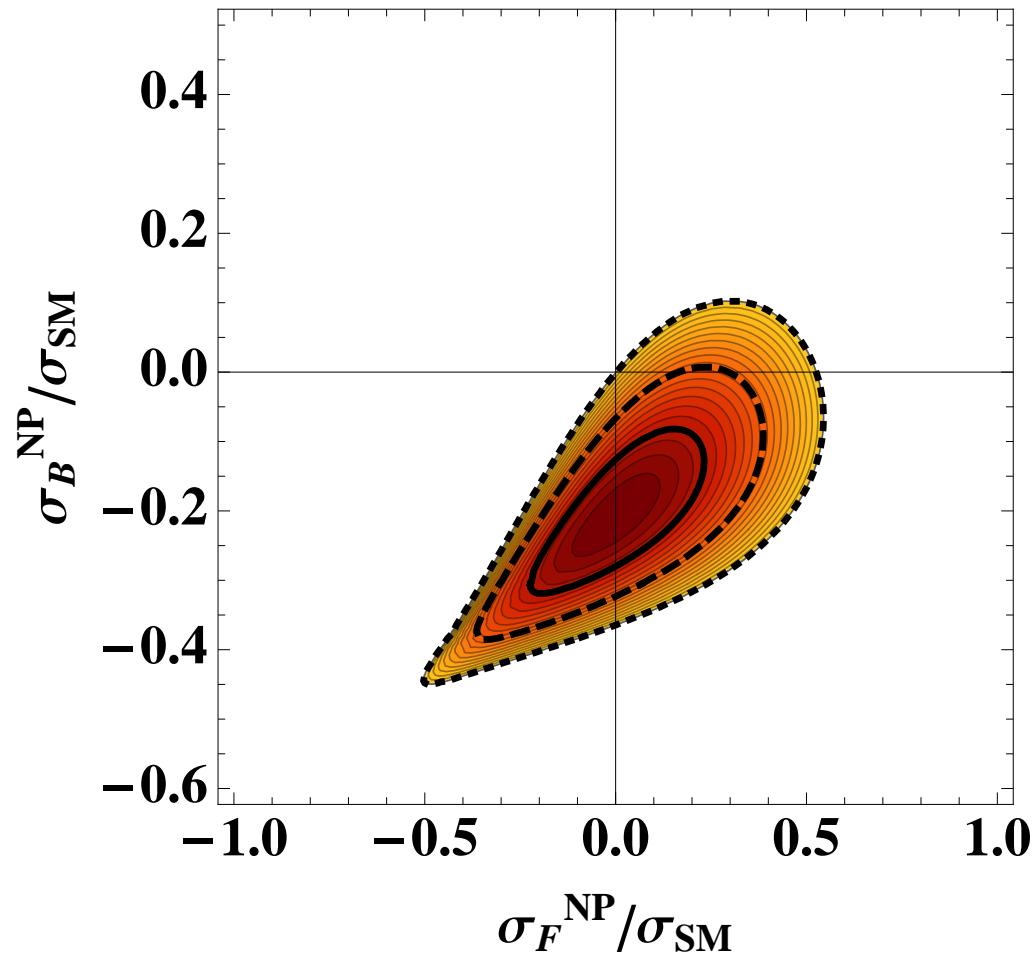
[Kuhn & Rodrigo, hep-ph/9807420]



**BSM**

Constraints:  $\sigma_{t\bar{t}}$ ,  $d\sigma/dm_{t\bar{t}}$ ,  $A_{FB}$ , dijets, flavor,  $Z \rightarrow b\bar{b}$ , etc.

# New physics contribution to rate



[J. Zupan, update of 1102.3374]

- Data prefer if there is interference between SM and BSM contributions



# New physics — model independently

- Consider higher dimension operators:  $\mathcal{H}_{\text{eff}} = \sum \frac{C_{i,N}}{\Lambda^N} \mathcal{O}_{i,N}$   
 $\Lambda$  cannot be much above the TeV scale to accommodate large effect at Tevatron
- $N = 1$ : (c)EDM, (c)MDM type operators – no effect on  $A_{\text{FB}}$
- $N = 2$ : 18 four-quark operators (for  $u\bar{u}$  initial state), only two interferes with SM:

$$\mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t), \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu\gamma_5 T^a u)(\bar{t}\gamma^\mu\gamma_5 T^a t)$$

Enough freedom:  $dA_{\text{FB}}/dm_{t\bar{t}} \propto C_A^8$ ,  $d\sigma/dm_{t\bar{t}} \propto C_V^8$

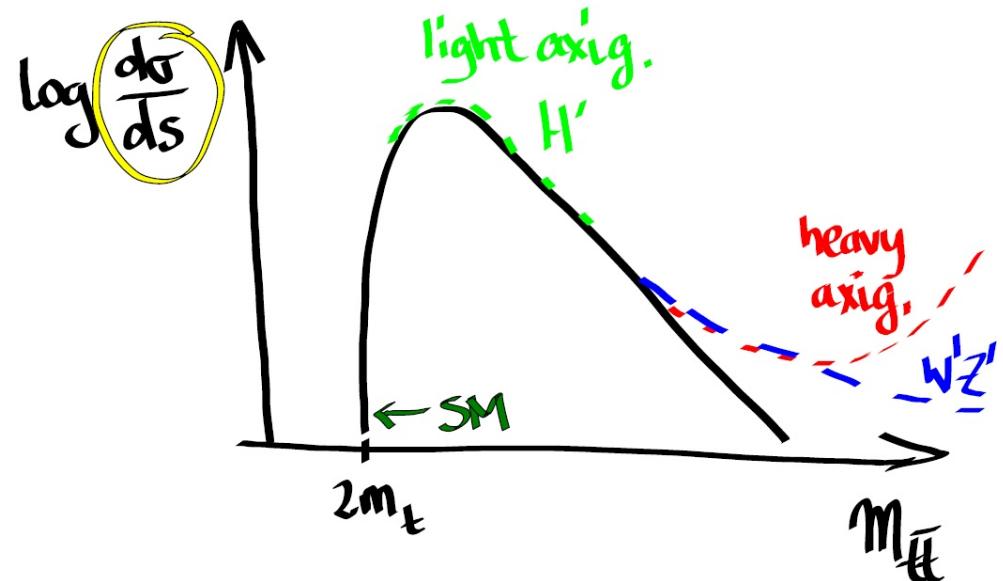
- In preferred parameter region  $(1/\Lambda^2)^2$  terms not negligible, neither are  $1/\Lambda^4$   
Moreover, want to study  $d\sigma/dm_{t\bar{t}}$  up to  $m_{t\bar{t}} \sim 1 - 2 \text{ TeV}$
- Effective theory framework not really useful  $\Rightarrow$  a model builders' paradise...!



# Model building preliminaries



all fit "reasonably" well:  $A_{t\bar{t}}, \sigma_{t\bar{t}}$



- Strong flavor bounds on  $t$  and  $u$  channel models ( $D - \bar{D}$  mixing) [Hitoshi *et al.*, 0907.4112]
  - A  $Z'$  would need to couple almost exclusively to  $ut$  mass eigenstates
- Strong bounds on same sign top production
- $W', Z'$  give less central  $t\bar{t}$  than scalars, less conflict with  $d\sigma/dm_{t\bar{t}}$  [Zurek *et al.*, 1103.3501]
- No one has the necessary information to perform a real  $\chi^2$  fit to any model

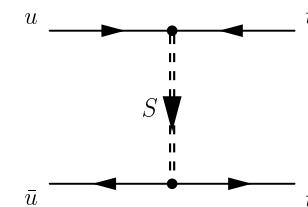


# An example + flavor symmetries

- Consider a “diquark”,  $\Delta(3, 1)_{-4/3}$ , coupling to  $u_{Ri}$  (anticipating flavor issues)

$$\mathcal{L} \sim g_{ij} \varepsilon_{abc} u_{Ri}^a u_{Rj}^b \Delta^c + \text{h.c.}$$

Typical parameters:  $m_\Delta \sim 400 \text{ GeV}$ ,  $g^{ut} \sim 1$



$D - \bar{D}$  mixing at one-loop  $\Rightarrow g^{ct} < \text{few} \times 10^{-3}$ , and also strong dijet constraints

- Can largely evade these bounds by considering flavor conserving models:

$$\mathcal{L} \sim \varepsilon^{ijk} \varepsilon_{abc} u_{Ri}^a u_{Rj}^b \Delta_k^c + \text{h.c.}$$

Now  $\Delta$  is both color and flavor triplet, can think of it as carrying flavor through

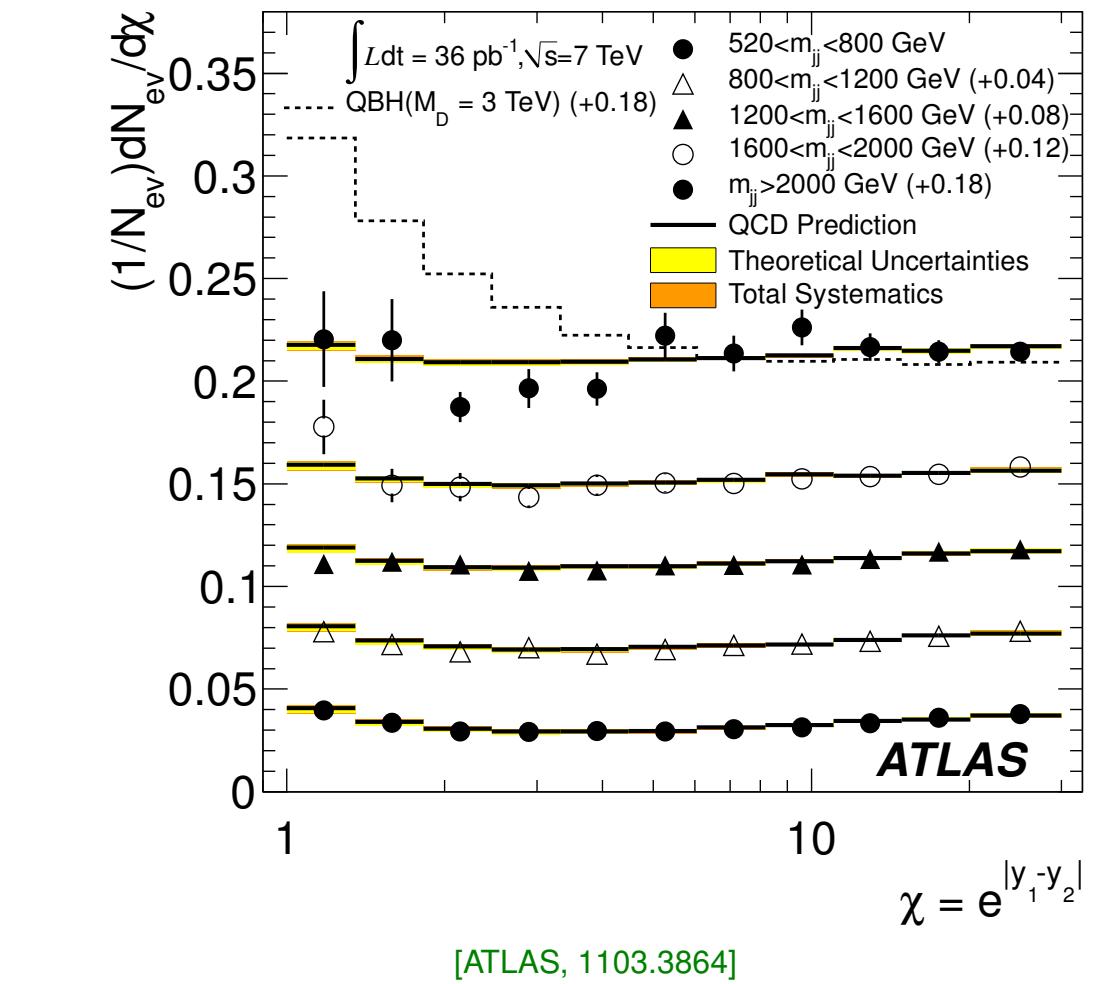
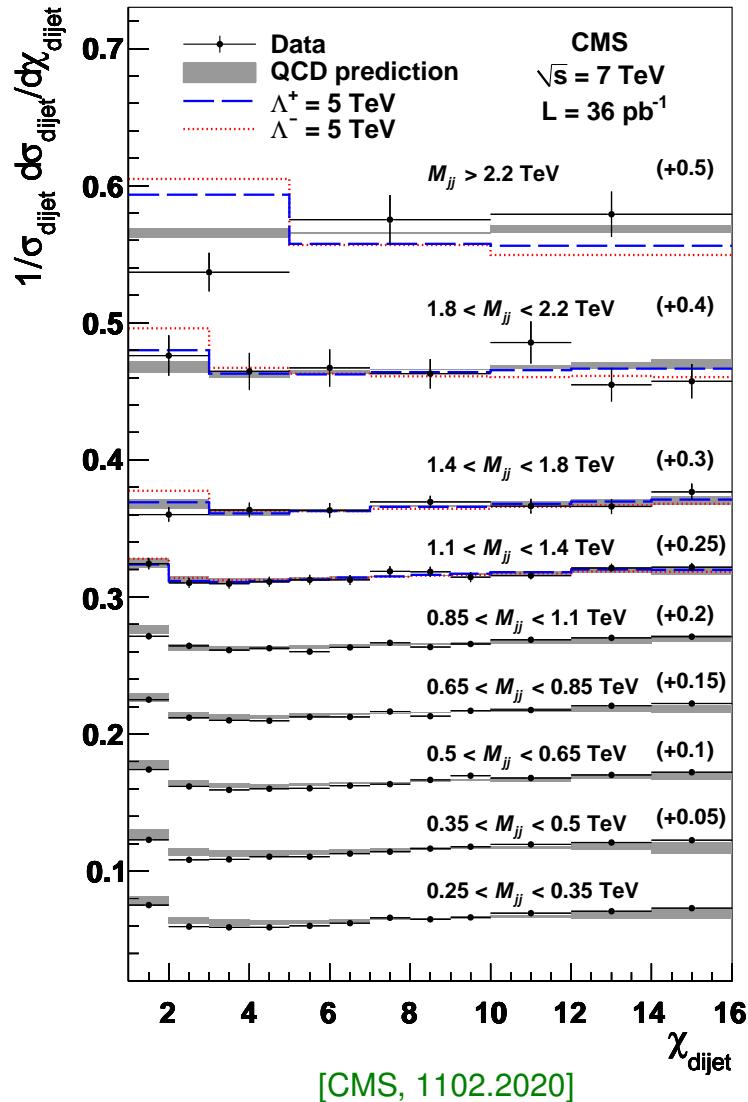
$\Rightarrow$  no FCNCs; no  $qq \rightarrow q'q'$  dijet signatures, only smaller  $uc \rightarrow uc$

[ZL, Schmaltz, Tavares, arXiv:1103.2757]

- A flavor and color triplet scalar can fit all data well and predicts rich LHC signals

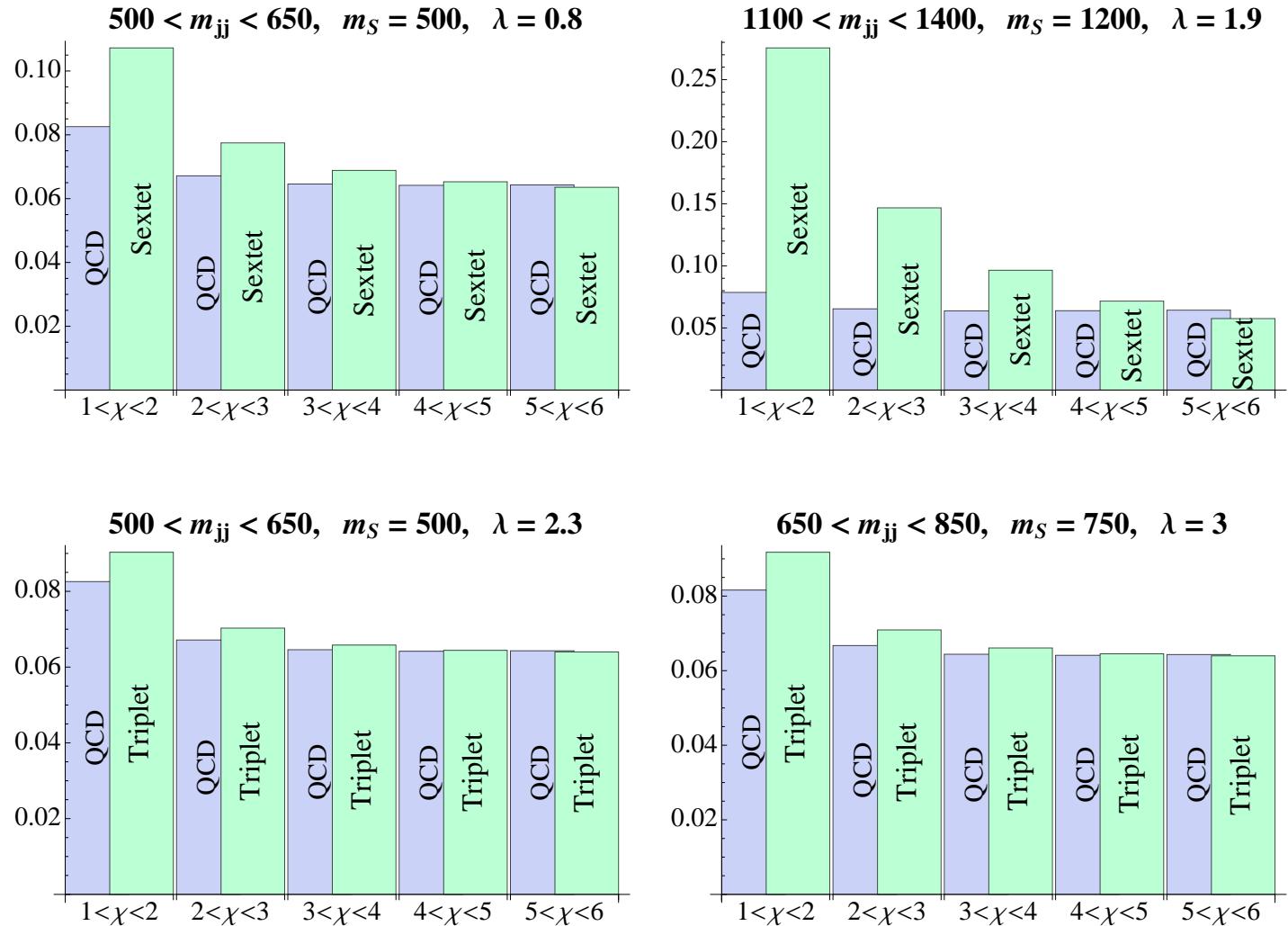


# Dijet distributions with $36 \text{ pb}^{-1}$



# (No?) dijet anomalies from resonances

- A flavor universal sextet is ruled out... by a lot...



[ZL, Marques Tavares, Schmaltz, 1103.2757]



# Other possibilities

- Light axigluons, in the ballpark of 450 GeV: If lighter than other new particles, decay to SM, would be narrow, but no bump in  $t\bar{t}$  mass spectrum  
⇒ Need to make it broad — “designer widths”

[Marques Tavares & Schmaltz, 1107.0978]

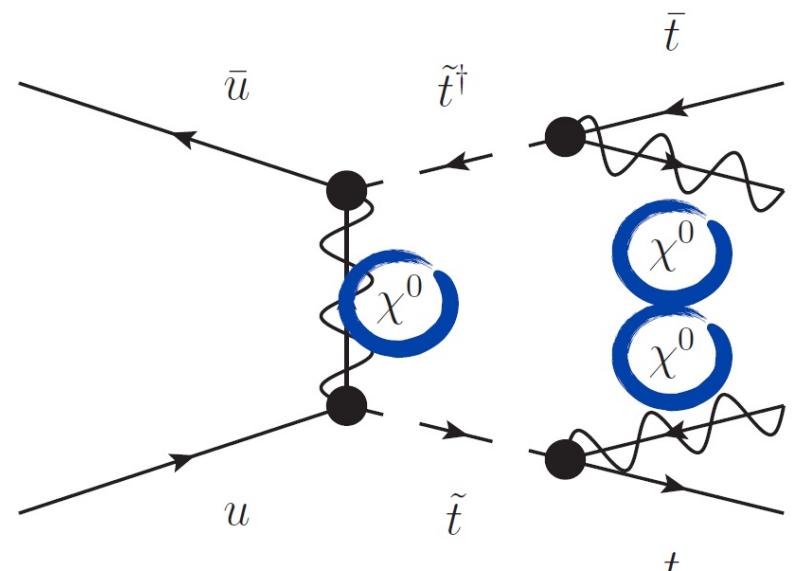
Signatures: pair production → 4 jets, 6 jets, 8 jets, 12 jets, each with 10s of pb

- “Incoherent” scenarios: e.g., anomalous stop pair production

$$\mathcal{L} \sim \tilde{Y}_q \bar{q}_R \tilde{t} \chi^0 + \text{h.c.}$$

Can fit data:  $m_{\tilde{t}} \sim 200$  GeV,  $m_{\chi^0} \sim$  few GeV,  
 $\tilde{Y}_t \sim 4$ ,  $\tilde{Y}_u \sim 1.5$

This is certainly not the MSSM...



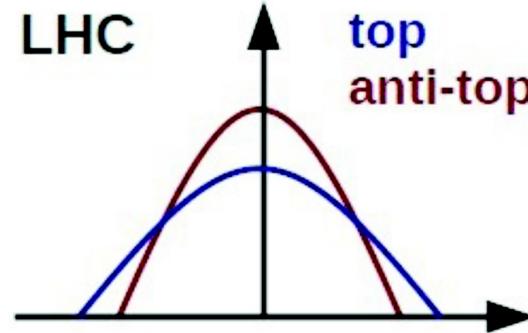
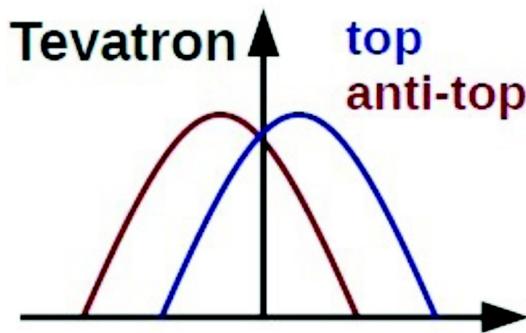
[Isidori & Kamenik, 1103.0016]



# **Asymmetry at the LHC**

# Charge asymmetry at the LHC

- No forward-backward asymmetry at a symmetric collider
- Charge asymmetry:  $A_{FB} > 0 \Rightarrow$  higher rapidity  $t$  quarks than  $\bar{t}$ ,  $A_C \sim 1\%$  in SM



$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$

- Results in central region (systematic uncertainty may soon be limiting):

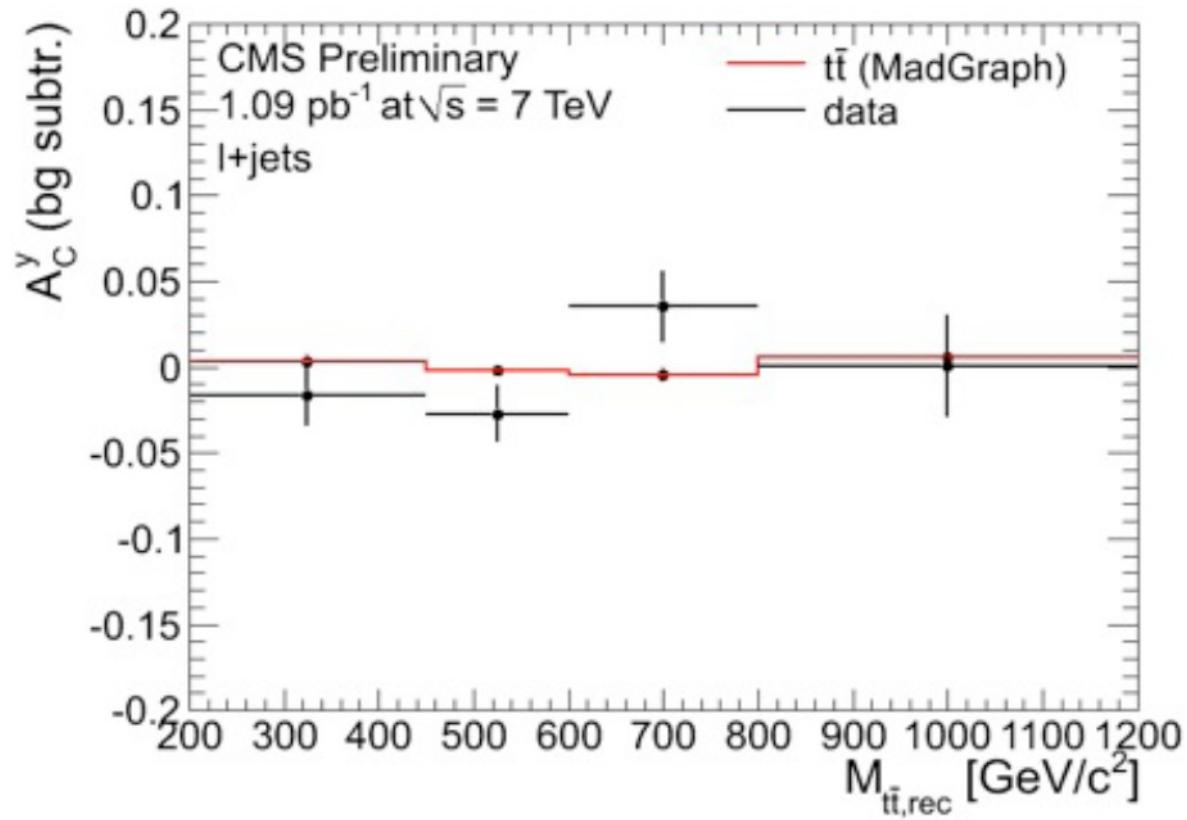
$$A_C = -0.024 \pm 0.016 \text{ (stat)} \pm 0.023 \text{ (syst)} \quad [\text{ATLAS-CONF-2011-106, } 0.7 \text{ fb}^{-1}]$$

$$A_C = -0.013 \pm 0.026 \text{ (stat)}^{+0.026}_{-0.021} \text{ (syst)} \quad [\text{CMS PAS TOP-11-014, } 1.09 \text{ fb}^{-1}]$$

- How to choose cuts (symmetric) to maximize sensitivity of the measurements?



## LHC: $m_{t\bar{t}}$ dependence of $A_C$



- No  $m_{t\bar{t}}$  dependence seen, but not yet unfolded; not clear if it contradicts CDF



# Boosting the LHC signals

- Can only use dominance of quark PDFs at large  $x$  (rather than antiquark or gluon)  
⇒ high  $m_{t\bar{t}}$  and/or boosted events

So far only central detectors used for  $t\bar{t}$  analyses ( $b$  jet and lepton tagging)

- Enhancement of the  $d\sigma/dm_{t\bar{t}}$  at large  $m_{t\bar{t}}$ , by a factor 2 [3] above the SM for  $m_{t\bar{t}} > 1 \text{ TeV}$  [1.5 TeV] — however, the efficiency is  $10^{-2}$  [ $10^{-3}$ ] [many papers]
- Forward going tops at LHCb [Kagan, Kamenik, Perez, Stone, 1103.3747]
  - ... control backgrounds if only one top is seen
- Reconstruct one top in central, one in forward detector [Arguin, Freytsis, ZL, 1107.4090]
  - ... forward calorimeter resolution worse than central
- $t\bar{t}$  events boosted in the  $z$  direction [Wang, Xiao, Zhu, 1008.2685; Aguilar-Saavedra, Juste, Rubbo, 1109.3710]
  - ... acceptance, efficiency, as above



# Our proposal

- LHC: no forward-backward asymmetry, but charge asymmetry as a function of rapidity sensitive to same physics

Tevatron:  $q\bar{q} \rightarrow t\bar{t}$  dominates

LHC:  $gg \rightarrow t\bar{t}$  dominates, no asym.

- New idea to enhance role of  $q\bar{q}$

[Arguin, Freytsis, ZL, arXiv:1107.4090]

$$R_1 : |\eta_{1,2}| < 2.5$$

$$R_2 : |\eta_1| < 2.5 \text{ and } |\eta_2| < 4.5$$

$$R_3 : |\eta_1| < 2.5 \text{ and } 2.5 < |\eta_2| < 4.5$$

$$M_1 : m_{t\bar{t}} > 450 \text{ GeV}$$

$$M_2 : m_{t\bar{t}} > 550 \text{ GeV}$$

- Significantly increases LHC sensitivity to these models with 2011–2012 data

Cuts	SM MCFM	new physics models		
		$Z'$	Axigluon	Scalar 3
$R_1$	$A_c = 0.011$	$A_c = 0.019$ $\varepsilon = 0.77$	$A_c = 0.025$ $\varepsilon = 0.78$	$A_c = 0.038$ $\varepsilon = 0.79$
$R_2$	$A_c = 0.018$	$A_c = 0.034$ $\varepsilon = 0.95$	$A_c = 0.031$ $\varepsilon = 0.94$	$A_c = 0.044$ $\varepsilon = 0.95$
$R_3$	$A_c = 0.028$	$A_c = 0.10$ $\varepsilon = 0.18$	$A_c = 0.058$ $\varepsilon = 0.17$	$A_c = 0.072$ $\varepsilon = 0.16$
$R_1 \& M_1$	$A_c = 0.018$	$A_c = 0.038$ $\varepsilon = 0.44$	$A_c = 0.040$ $\varepsilon = 0.42$	$A_c = 0.059$ $\varepsilon = 0.48$
$R_2 \& M_1$	$A_c = 0.021$	$A_c = 0.064$ $\varepsilon = 0.54$	$A_c = 0.046$ $\varepsilon = 0.50$	$A_c = 0.068$ $\varepsilon = 0.57$
$R_3 \& M_1$	$A_c = 0.037$	$A_c = 0.18$ $\varepsilon = 0.10$	$A_c = 0.080$ $\varepsilon = 0.082$	$A_c = 0.12$ $\varepsilon = 0.087$
$R_1 \& M_2$	$A_c = 0.022$	$A_c = 0.075$ $\varepsilon = 0.21$	$A_c = 0.061$ $\varepsilon = 0.19$	$A_c = 0.089$ $\varepsilon = 0.25$
$R_2 \& M_2$	$A_c = 0.029$	$A_c = 0.12$ $\varepsilon = 0.27$	$A_c = 0.10$ $\varepsilon = 0.22$	$A_c = 0.10$ $\varepsilon = 0.29$
$R_3 \& M_2$	$A_c = 0.041$	$A_c = 0.29$ $\varepsilon = 0.057$	$A_c = 0.10$ $\varepsilon = 0.036$	$A_c = 0.16$ $\varepsilon = 0.041$



# Conclusions

- Large forward-backward asymmetry would be unambiguous sign of new physics  
DØ neither strengthens nor rules out CDF claim, average asymmetry also large
- ATLAS/CMS results (charge asymmetry,  $d\sigma/dm_{t\bar{t}}$ ) not yet sensitive enough
- Several proposals how to optimize LHC experiments' sensitivities
- The LHC should be able to test many of the proposed models by a combination of (not yet implemented) cuts

